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TITLE: MEASURING SPHERICITY ON A ROUNDNESS GAGE

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MEASURING SPHERICITY ON A ROUNDNESS GAGE

by

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ABSTRACT

The three-dimensional geometry of a spherical object may be determined by evaluation of a number of two- dimensional roundness measurements bearing a known orientation with respect to one another. A suitable set of orientations appears to be one in which the plane of each roundness measurement coincides with every other such plane along a single diameter of the sphere. A device for producing the required set of orientations, adaptable to spheres of varying diameters and designed to avoid damage to delicate materials, has been developed and tested.

I. INTRODUCTION

A problem frequently encountered at the Los Alamos National Laboratory is that of measuring various aspects of the surface topography of a spherical object. Oftentimes, a measurement of "surface finish" and some number of roundness measurements will provide sufficient information for practical purposes.

As the ability to manufacture better spheres increases, however, the need for more complete information grows, leading inevitably toward the desire for a total description of the geometry of the three-dimensional surface in space.

In working toward such a complete description, it may prove useful to consider the surface as being the sum of many components varying in wavelength and amplitude. The components at the short wavelength end of the spectrum comprise what has traditionally been called surface finish, and can be measured by the methods (stylus , optical interference, etc.) developed for surface finish assessment. Because of its complexity, an assessment of the surface finish of the entire sphere is rarely attempted (though work is being done in this direction), and instead a sampling technique is chosen, whereby some number of areas are assumed to be representative of the whole.

As the wavelength of the component of interest increases, it enters the realm of "waviness". Components with a wavelength significantly less than the circumference of the sphere can be assessed by inspection of individual roundness measurements of known orientation with respect to the sphere. Here, again, a sampling technique is often used, simply because of the mass of information available.

As the wavelength of the component of interest approaches the circumference of the sphere, the sampling method becomes less capable of adequately describing the surface, which is three- dimensional. One is therefore lead to consider ways of more completely describing the large-scale three-dimensional geometry of the sphere, which may be termed its sphericity.

II. MEASURING ROUNDNESS

Consider first roundness and how it is measured. In principle, the roundness of an object is simply the deviation between the curve formed by the intersection of its surface with a chosen plane (the plane of measurement), and a perfect circle (see Fig. 1). In practice, roundness is measured by comparison with the motion of a precision spindle. Either the object under test is rotated and deviations are observed with a stationary gage head (the "rotating workpiece" type roundness gage; see Fig. 2), or the object is held stationary and the gage head is rotated around it (the "rotating gagehead" type roundness gage; see Fig. 3). Deviations from roundness are usually recorded on a polar chart.

III. MEASURING SPHERICITY: THEORY

To arrive at a description of the three-dimensional geometry of a sphere by use of two-dimensional roundness measurements, it is clearly necessary to make roundness measurements in more than one plane. One common technique is to rotate the sphere in a random fashion after each roundness measurement, and make several such measurements. While perhaps acceptable for the purpose of obtaining a general idea of the maximum deviation from sphericity, this method fails to provide any information about the actual shape of the surface. Its failure to do so stems from lack of knowledge of the orientation of the roundness measurements.

In order to map the surface, it is necessary to make roundness measurements at known orientations with respect to one another. Since the roundness gage itself is fixed, the sphere must be rotated between roundness measurements in order to change the plane of measurement.

In what manner should the sphere be rotated? Figure 4 shows one possibility; here the sphere has been rotated alternately about three orthogonal axes. This method might even be extended to rotation about "n" non-orthogonal axes. Such a method has an advantage when one is assessing waviness, in that it provides measurements of the surface in many different orientations. In concept, it should be possible to take a collection of measurements like this and say something about the sphericity of the sphere. However, the mathematics of doing so are somewhat formidable. In addition, the procedure for rotating the sphere must be carefully designed to avoid duplicating measurements made when the sphere is rotated about one axis with those made when it is later rotated about another.

Another possibility is illustrated in Figure 5. Here, all rotations of the sphere are made about one axis, and all roundness measurements pass through the poles of this axis. It is much easier to visualize how these measurements might be used to define the shape of the sphere. In the simplest case, one might set the polar chart recordings side by side and compare them; or they might be overlayed. Because all roundness measurements pass through one diameter (the axis about which the sphere is rotated), it is an easy matter to measure this diameter and use it to calculate the diameter at any other location on the sphere. If further analysis is desired, the mathematical description of the surface, given the (digitized) roundness measurements, is straightforward (References 1,2). From this description, parameters such as the minimum radial separation of two concentric spheres required to contain the surface (corresponding to the MRS for roundness) can be determined. Because of its simplicity and versatility, this latter approach has been chosen for the design of the sphericity gage at Los Alamos.

Having chosen the general scheme for evaluating sphericity, one is left with the need for deciding how many roundness measurements are required; i.e., what angle to rotate the sphere through between measurements. A complete description of the sphere geometry, of course, would require an infinite number of measurements, and the greater the number of measurements the greater the reliability of the final result. In the interest of efficiency, however, the fewer measurements the better. As a compromise, it was decided to limit the number of measurements in most cases to the minimum that would allow no defect to go undetected when the surface, after being characterized by means of the sphericity gage, was later inspected with a microscope. Since the field of view of the microscope used is about 0.5 mm, this means the number of measurements required is no less than (half the ball circumference divided by 0.5 mm). Using this spacing assures that at their widest spacing, which occurs at the equator of the sphere, the roundness measurements are no more than 0.5 mm apart.

IV. A PRACTICAL SPHERICITY GAGE

The roundness gage chosen for use in this project was of the rotating gagehead design, in which the sphere is held stationary on a work platform and the gage head is rotated about it (see Fig. 3). The work platform may be moved vertically and horizontally to center the sphere beneath the precision spindle.

The device required to align the sphere and rotate it about one given axis by exact, known angular increments (which, as described above, is necessary in order to use roundness measurements to describe sphericity) is shown in Figure 6. This device will be referred to as the sphericity attachment. It consists of a vertical axis rotating vacuum chuck and a horizontal axis vacuum chuck with rotary and translational motions, both mounted on a base plate that rests on the work table of the roundness gage.

The vertical axis vacuum chuck assembly is shown in Figure 7. The primary purpose of this assembly is to hold the sphere in a fixed position during the time a roundness measurement is being made. The chuck itself is a brass body with a conical teflon insert at the tip. Vacuum is applied through a central hole in the chuck, which allows atmospheric pressure to seat the sphere under test firmly against the conical insert. Teflon was chosen as the material for the insert in order to avoid damaging the sphere. Initially, an all-teflon chuck was envisioned, but it proved to be too unstable to hold the sphere motionless during a roundness measurement.

The chuck is mounted on a ball-seat wobble plate which is attached to a rotary table. The wobble plate, shown in greater detail in Figure 8, is a commonly used device which provides very precise centering capability; it is used here to center the sphere about the axis of the rotary table. For alignment purposes, the sphere to be tested is placed in the chuck, and its runout is measured as the rotary table is rotated, using a stationary indicator.

Rough adjustments are made by loosening one of the adjusting screws (Fig. 8) and tightening the opposing screw, which causes the plate attached to the chuck to rotate as a rigid body with respect to the other plate. Fine adjustments are then made by tightening one screw without first loosening its opposite; this deforms the plate slightly, causing a small angular motion of the chuck. With this arrangement, runout of the sphere can be reduced to 0.25 micrometer TIR or less.

The horizontal axis vacuum chuck assembly, shown in Figure 9, is identical to the vertical axis assembly, but it is mounted on three orthogonal micrometer slide tables in such a way as to allow rectilinear motion in three directions. In addition, an all-teflon chuck is used (rather than brass with a teflon insert), as extreme stability is not required. The axis of rotation of this chuck assembly defines the common axis through which all roundness measurements must pass (see Fig. 5).

Because the diameter of the sphere to be measured may vary , both the horizontal and vertical vacuum chucks have been designed to be easily removed from their respective assemblies. If necessary, a set of chucks may be designed for every sphere diameter encountered. This capability adds greatly to the flexibility of the sphericity gage.

V. ALIGNMENT

Prior to use, the sphericity attachment and roundness gage must be aligned. The purpose of this alignment is to ensure that the axes of the vertical chuck rotary table, horizontal chuck rotary table, and the roundness gage spindle will coincide at a point; and that a sphere of the size to be tested, held in either the vertical or horizontal chuck, will be centered about this point.

The initial step in alignment is to set the center of the sphere, when held first in the horizontal and then in the vertical vacuum chuck, on the axis of rotation of each chuck. This is accomplished using the webble plate on each chuck assembly and a stationary indicator, as described earlier.

The axis of rotation of the roundness gage spindle is then made to coincide with that of the vertical axis vacuum chuck. The roundness gage spindle, with its gage head contacting the sphere (still mounted in the vertical chuck), is rotated 360 degrees and the offset of the center of the resulting roundness measurement is observed. The entire sphericity attachment is then moved in the horizontal plane by means of adjustments on the roundness gage work platform until the sphere is centered beneath the roundness gage spindle. At this point the axis of the roundness gage spindle and that of the vertical chuck assembly coincide and pass through the center of the sphere. The work platform of the roundness gage is then moved vertically until the roundness gage indicates that the maximum diameter of the sphere has been reached; the plane of measurement is now a horizontal plane passing through the center of the sphere.

Finally, the axis of the horizontal chuck assembly must be made to pass through the center of the sphere. The sphere is placed in the horizontal chuck, and the offset of its center from the axis of the roundness gage spindle is again observed by rotating the spindle. The sphere is centered on this axis by moving the chuck assembly in the horizontal plane using its micrometer slide tables. The vertical micrometer slide table is then used to lower the sphere until it just contacts the vertical chuck.

At this point the sphere, when held in either the vertical or horizontal chuck assembly, will occupy the same position with respect to the roundness gage, and the axis of the horizontal chuck assembly lies in the plane of measurement of the roundness gage. The micrometer readings of the three horizontal chuck assembly slide tables are noted, the sphere is transferred to the vertical chuck, and the horizontal chuck is backed out of the way.

VI. OPERATION

Operation of the sphericity gage may then proceed as follows: the gage head of the roundness gage is brought into contact with the sphere, and the roundness gage spindle is rotated until the gage head is opposite the horizontal spindle; this location is designated the south pole of the sphere. It lies at the intersection of the horizontal vacuum chuck axis of rotation (which passes through the center of the sphere) and the surface of the sphere opposite the horizontal chuck. The intersection of this axis and the side of the sphere facing the horizontal chuck is termed the north pole. A roundness measurement is made, and the angular position of the north pole is marked on the resulting polar chart recording.

The sphere must now be rotated about the axis passing through its north and south poles. This axis will be referred to as the polar axis. To rotate the part, the horizontal vacuum chuck is brought back into contact with the sphere by adjusting its three micrometer slide tables back to their previously noted positions. The sphere is transferred to this chuck and raised off the vertical chuck (again using the slide tables). The horizontal axis rotary table is rotated by the desired angle, and the sphere is lowered and transferred to the vertical chuck. Consider the situation at this point. Even assuming there is no rocking of the sphere during transfer to and from the horizontal chuck, if the sphere deviates at all from sphericity, it will locate in a different position of the conical seat of the vertical chuck than that it occupied during the first roundness measurement. That is, the polar axis, while still parallel to its original position, may be displaced vertically and horizontally from that position. The magnitude of this displacement may be on the order of the deviation from sphericity, or it may be larger, due to inaccuracies in the conical chuck seat.

Suppose another roundness measurement were made at this time. Since the plane of measurement is horizontal, small vertical offsets of the sphere's polar axis from its original location will cause negligible (cosine type) errors in the observed roundness. However, offsets in the horizontal plane will be observed directly, and could be misinterpreted as a bulge to one side of the axis.

Because the polar axis may have been offset, no information is lost by again moving the work platform of the roundness gage to center the part on the roundness gage spindle axis. This is done, and a roundness measurement is made. The angular position of the north pole on the resulting polar chart recording is known to be the same as its angular position in the original measurement, because the polar axis of the sphere is still parallel to its original position. However, the data may need to be shifted to one side of this axis by an as yet unknown amount to account for the polar axis being displaced horizontally from its original location.

The process of rotating, centering, and obtaining a roundness measurement is repeated until the required number of measurements is obtained. The angular orientation of all these roundness measurements with respect to one another is known--the polar chart recordings correspond directly. However, each may have to be shifted in a direction perpendicular to the polar axis; that is, in the plane of the equator of the sphere. The amount by which the data must be shifted can be determined if the shape of the equator of the part is known, since the points at an angular position of 90 degrees from the north pole on each longitudinal roundness measurement must lie on the equator at a known longitude.

For the measurement of roundness at the equator, the sphere is first rotated back to its original position, in which its polar axis lies parallel to the axis of the horizontal chuck and its north pole faces the chuck. In this position, zero degrees longitude lies in a horizontal plane and the equator of the part lies in a vertical plane. The sphere is then rotated 90 degrees about a horizontal axis and 90 degrees about a vertical axis (using, respectively, the horizontal and vertical vacuum chuck assemblies), bringing its equator into the horizontal plane with zero degrees longitude lying on the axis of the horizontal chuck and facing away from it. The work platform of the roundness gage is adjusted to center the sphere, and the roundness of the equator is measured.

VII. DATA REDUCTION

The roundness measurements may now be oriented correctly with respect to one another, as indicated in Figure 10. A simple technique for visual analysis of sphericity is to make transparencies of the longitudinal polar chart recordings and, shifting them when necessary as indicated by the equator roundness measurement, overlay them one on another. Such a composite is shown in Figure 11. Unfortunately, this simple method leaves much to be desired in terms of quantitative results.

VIII. TESTS OF SPHERICITY GAGE ACCURACY

As noted previously, the requirements for an accurate measurement of sphericity include provision of a way to rotate the sphere about its polar axis by a precisely known angle. The accuracy with which these rotations can be performed will determine ...

sphericity measurment. Three errors are possible: linear offset of the axis of rotation from the polar axis of the sphere, angular offset of the same axes, and errors in the angle through which the sphere is rotated about its polar axis.

The possibility that the axis of rotation may be parallel to the polar axis but offset from it has been considered and accounted for by making a roundness measurement at the equator of the sphere. The maximum angular offset of these axes and the maximum error in rotating about the polar axis must be included in calculating the uncertainty of the final measurement. Testing was therefore carried out to determine the magnitude of these angular errors.

For these tests, a very small spot (less than .018 inch in diameter) was engraved on a test sphere. If the axis about which the sphere is rotated is unchanging, and if the spot can be aligned (by eye) accurately enough on this axis, this spot should appear in every roundness measurement made during a standard measurement of sphericity. When this experiment was performed, the spot did indeed appear in every measurement. Calculations based on these results indicate that the axis of rotation did not vary by more than +/- 1.6 degrees of arc after eight separate transfers and rotations of the test sphere.

A second test designed to measure the accuracy of the angular increment through which the sphere is rotated was performed similarly, with the spot aligned this time at the equator of the test sphere. If the sphere is initially aligned so as to cause the spot to appear in the first measurement, it should again appear when roundness is measured after rotation to 180 or 360 degrees longitude. This test showed the accuracy of rotation to be +/- 1.6 degrees of arc or better after twelve separate transfers and rotations of 30 degrees.

IX. THE FUTURE

At least two possibilities exist for extension of the usefulness of the gage, both relating to data manipulation and both requiring digitization of the output of the gage. The first possibility, mentioned previously, is to digitize the data from each roundness measurement, and knowing the orientation of each measurement with respect to the others, redefine these points in terms of a common coordinate system. The best-fit sphere could then be calculated, and a map of contour deviations from this best-fit sphere produced.

A second possibility is to define more precisely the "spectrum" of wavelengths present on the sphere surface. This could be accomplished by digitizing data from both the surface finish (short wavelength) and roundness (longerwavelength) measurements and combining them to produce a statistically meaningful measure of wavelengths present, such as the power spectral density function.

X. CONCLUSION

A device allowing determination of the three-dimensional geometry of a spherical object by use of two-dimensional roundness measurements has been designed and tested, and is now in operation at Los Alamos. At present, the output of this sphericity gage is being evaluated by a simple comparison technique; even so, the information obtained represents a step beyond that available from randomly oriented roundness measurements. It is felt that the usefulness of the gage may be enhanced in the future by increased data manipulation.

XI. ACKNOWLEDGEMENTS

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XII. REFERENCES

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LIST OF FIGURES

Figure 1: The Concept of Roundness

~~Figure 2: "Rotating Workpiece" Type Roundness Gage~~

Figure 3: "Rotating Gagehead" Type Roundness Gage

Figure 4: Roundness Traces Made From Three Orthogonal Axes

Figure 5: Roundness Traces Made From One Axis

Figure 6: Sphericity Attachment

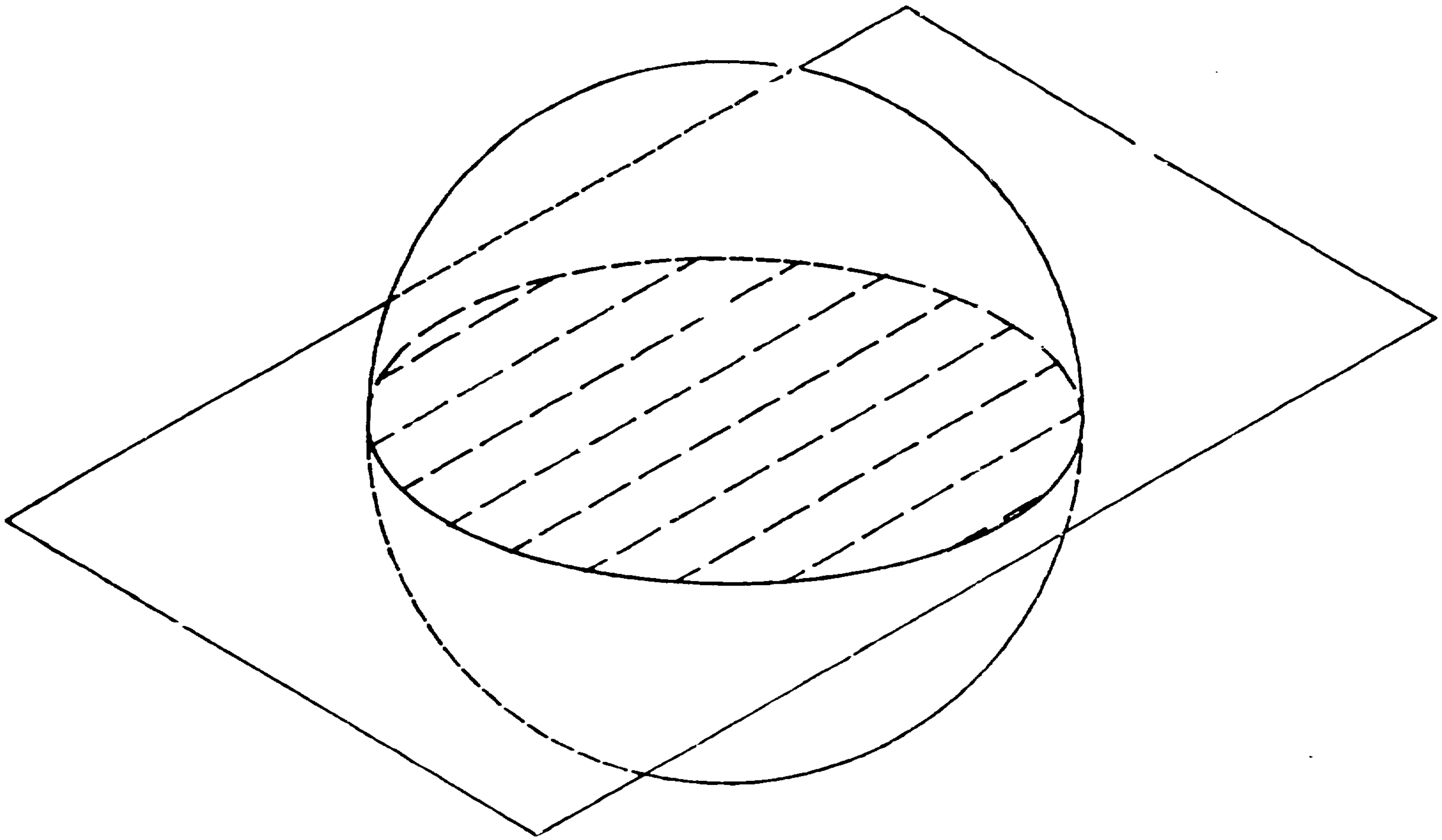
~~Figure 7: Vertical Vacuum Chuck~~

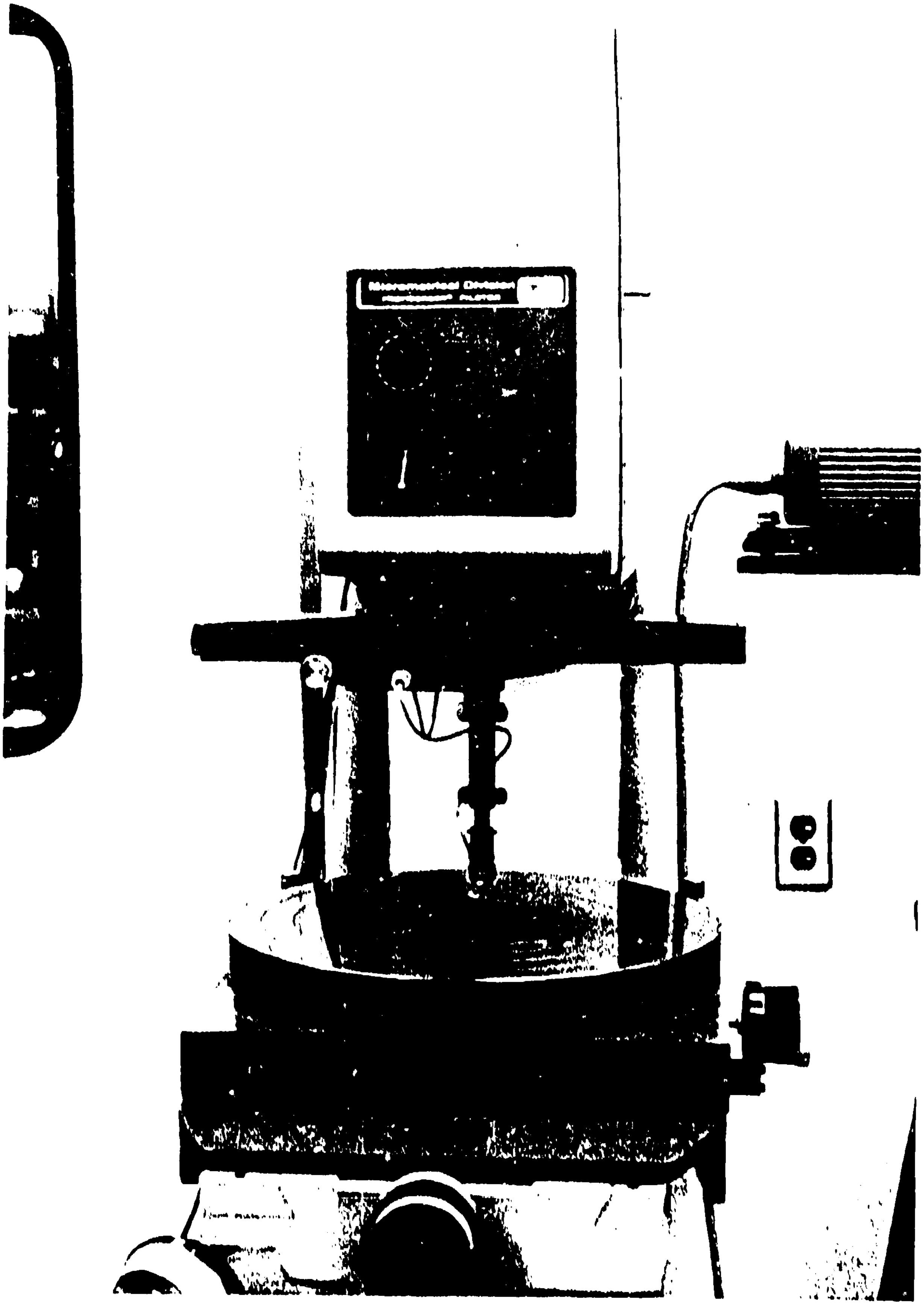
Figure 8: Horizontal Vacuum Chuck

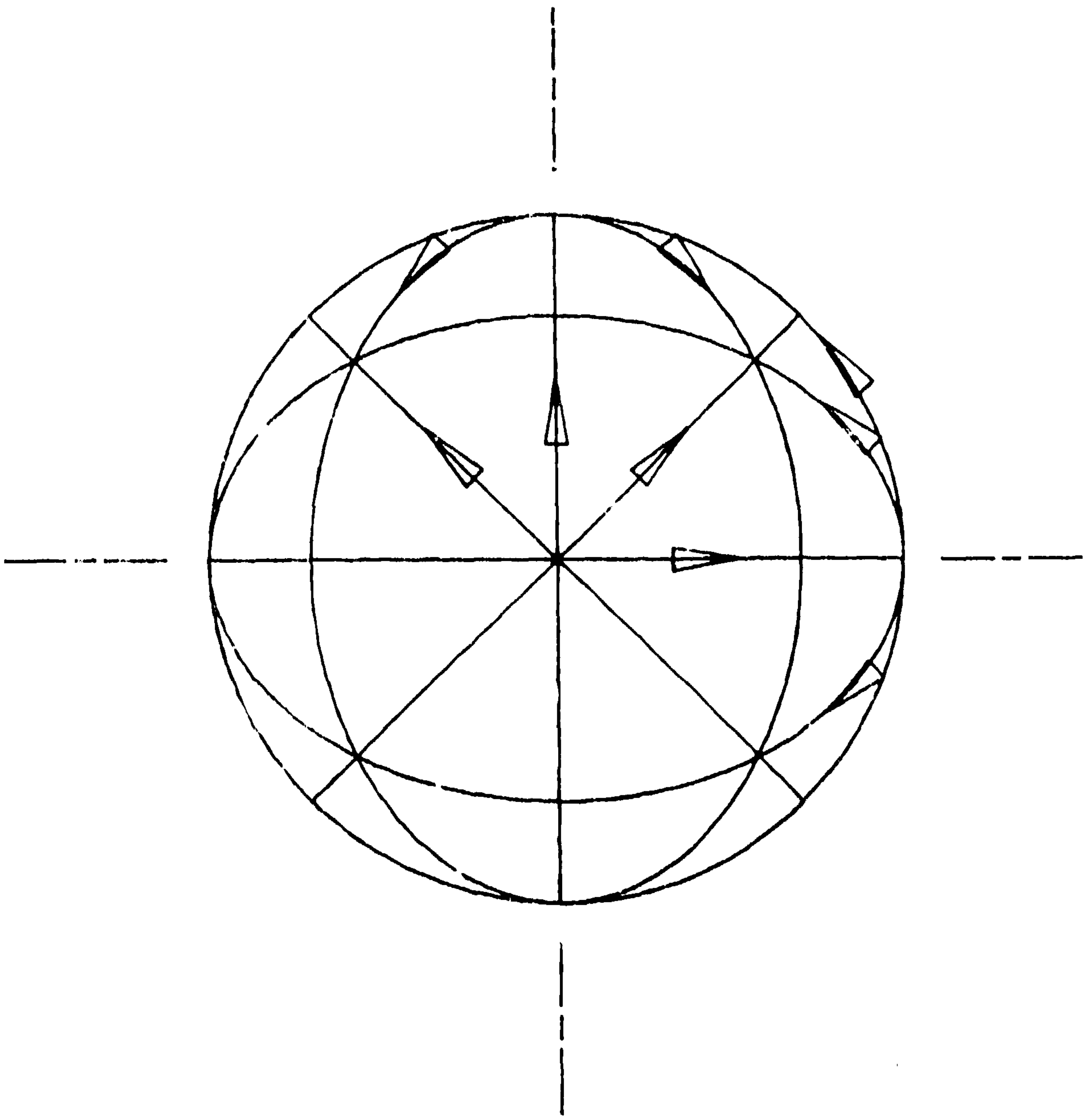
Figure 9: Wobble Plate Design

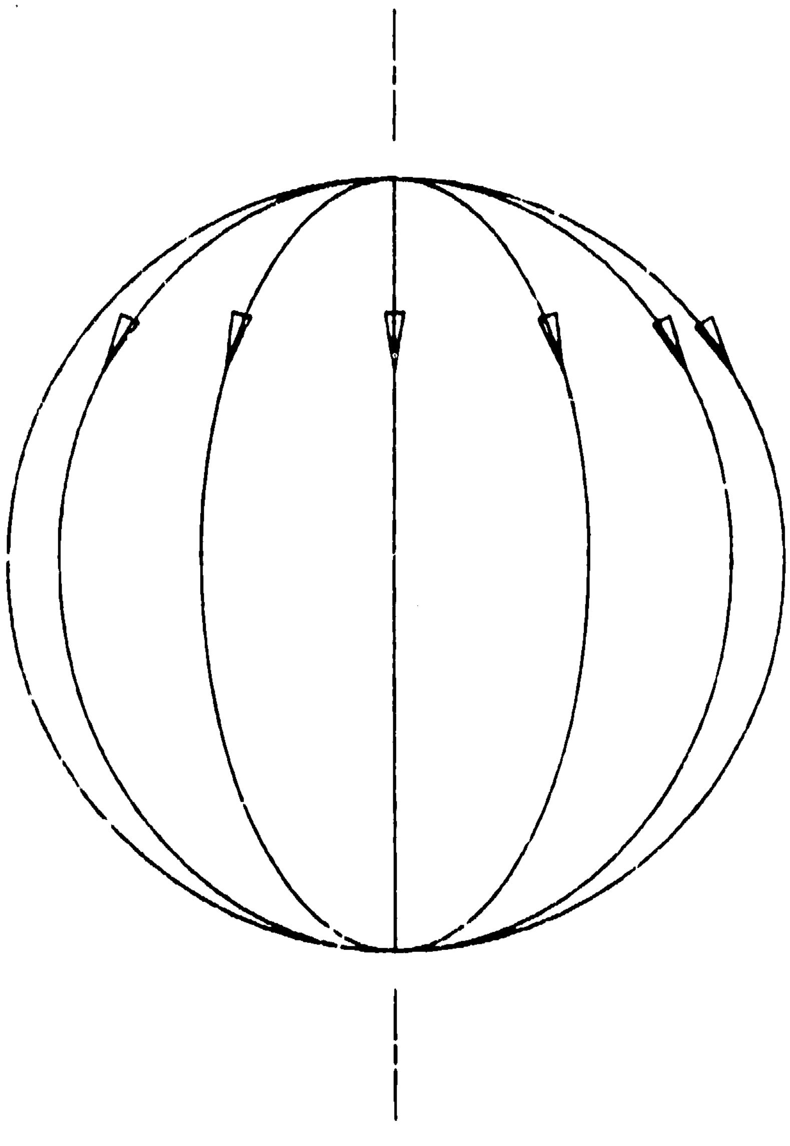
Figure 10: Orientation of Roundness Measurements to Describe Sphericity

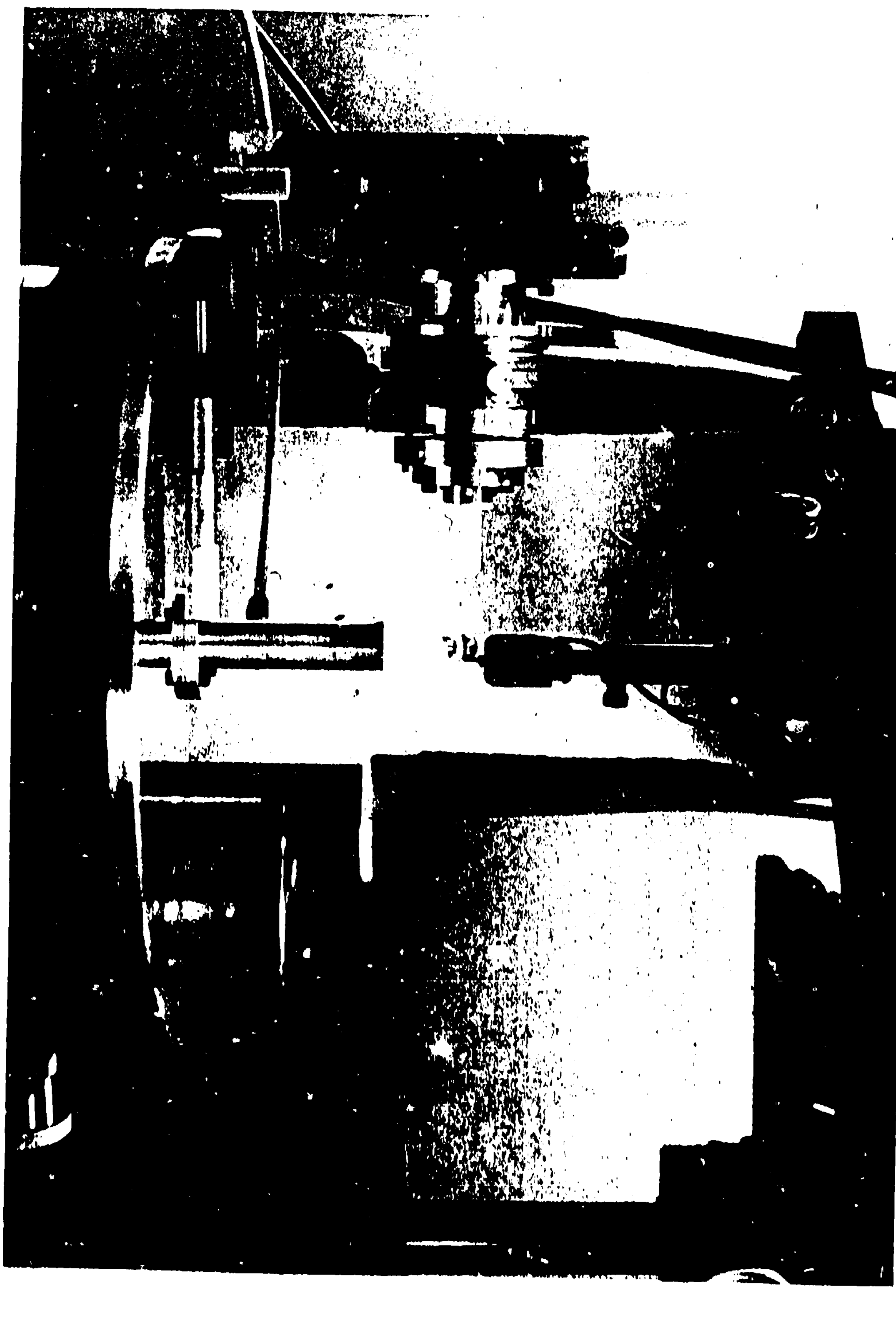
Figure 11: Overlay Longitudinal Roundness Measurements

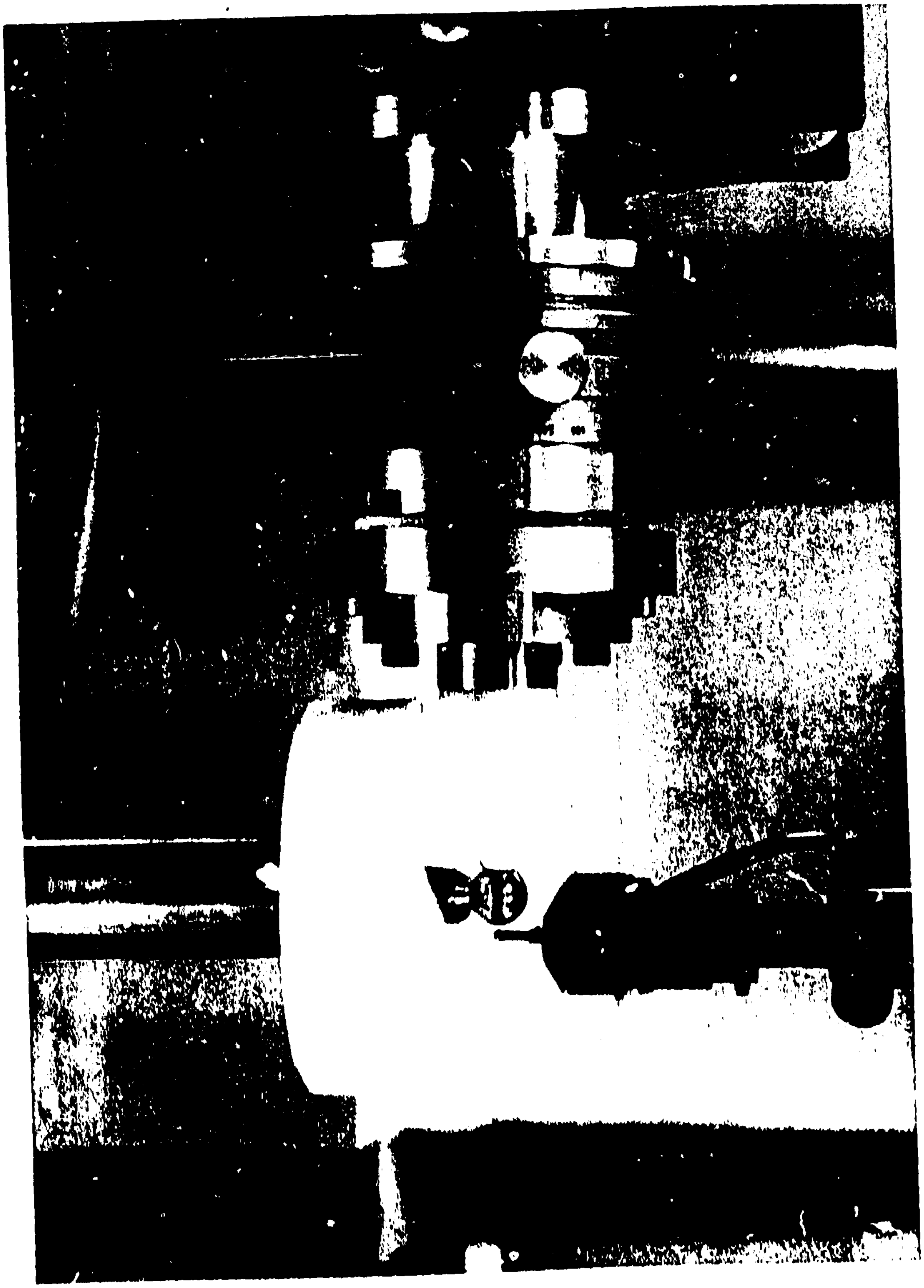


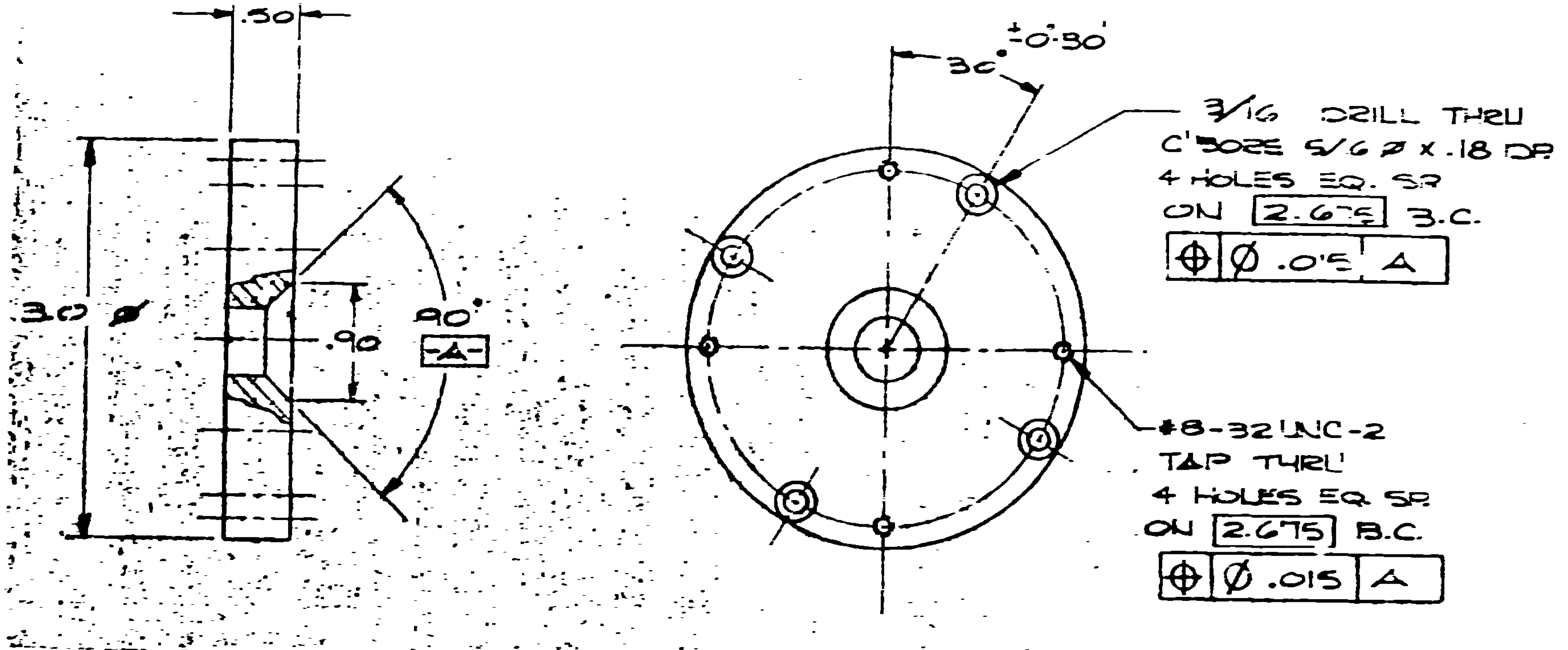








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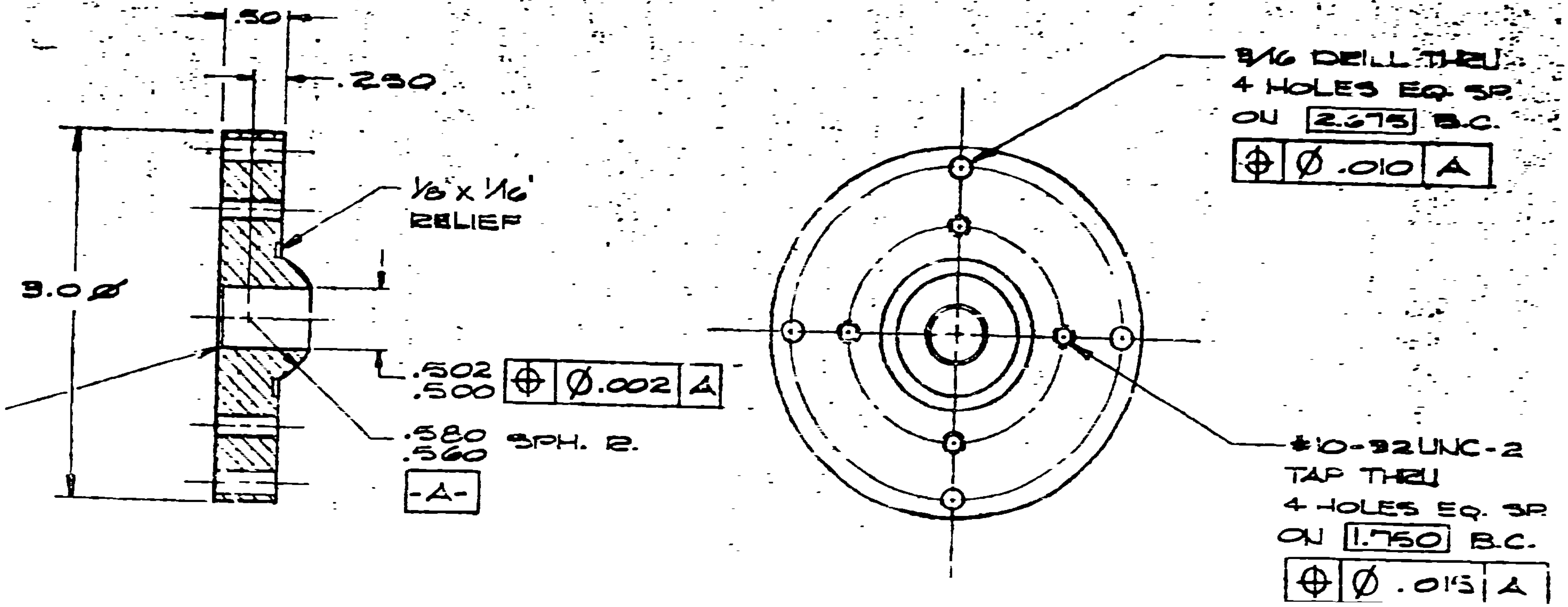
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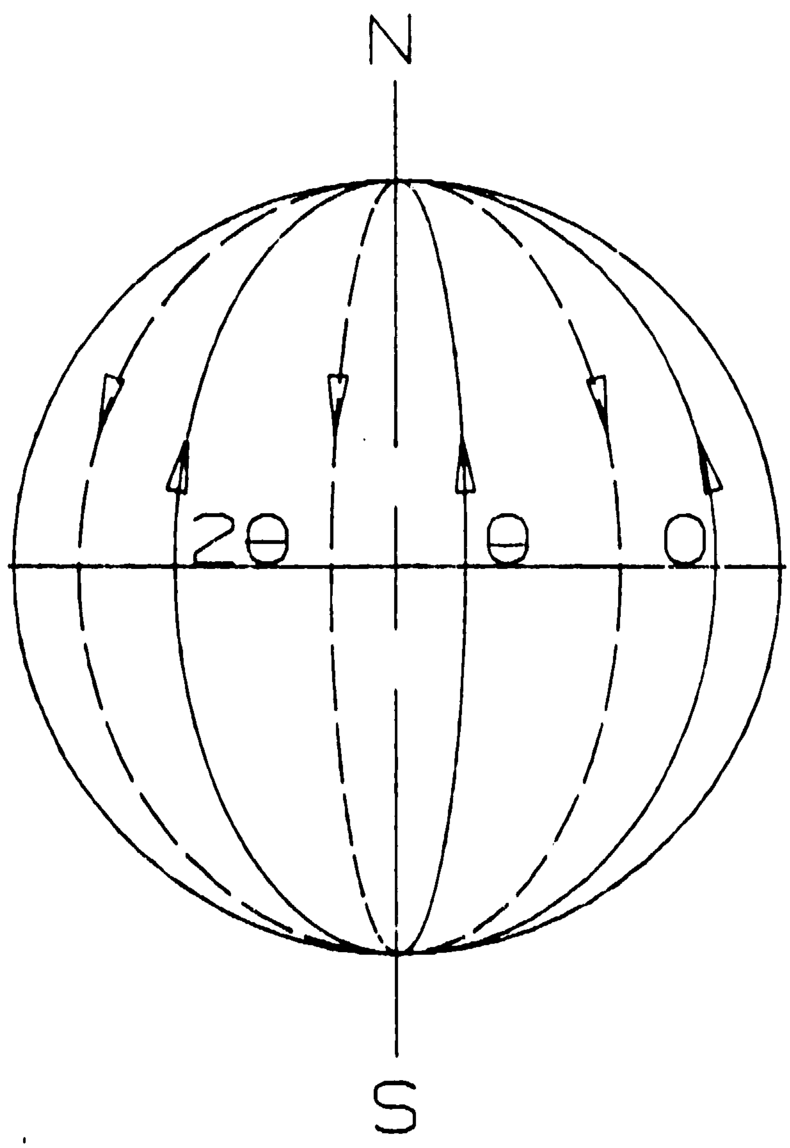
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